R. Kenneth Hutcherson, Stuart L. Moran
and E.D. Ball
Naval Surface Weapons Center
Code F12
Dahlgren, Va 22448

Introduction and Background

In an effort to extend the state of the art in pulsed power switching, experimental investigations of triggered spark gap switches have been performed. The goal is to develop a low-flow gas switch that holds off 100 kV; then conducts 10's of kA; and, after 100 microseconds, again holds off 100 kV.

Recovery time is defined as the minimum time from the first applied voltage waveform breakdown to the time the gap can hold off a a voltage equal to the first breakdown voltage. The recovery data in figure 1 is taken from earlier investigations of overvolted spark gap switching.[1] A voltage waveform is applied to the switch and the switch breaks down. Some time later, a second voltage waveform is applied to the switch and its breakdown voltage is recorded. Figure 1 is a plot of the second waveform breakdown voltage for different times between breakdown (henceforth called the delay time). These previous investigations have shown that unblown, overvolted spark gaps have recovery times of a few milliseconds. Hence, operating repetitive spark gap switches in the overvolted regime puts a severe limit on the rep rates at which such a switch can perform (Fig. 1).
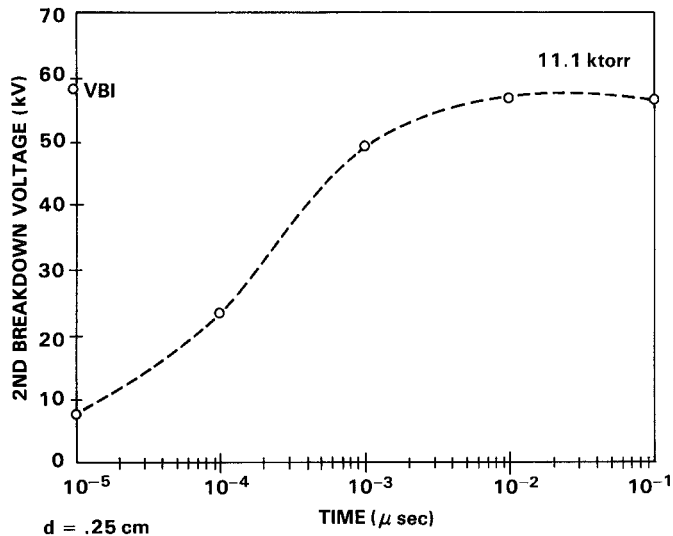

d = .25 cm

Figure 1: Recovery of overvolted H_2 spark gap. The symbol VB1 along the vertical axis indicates the first waveform breakdown voltage. Recovery time is on the order of milliseconds.

From figure 1, lowering the first

waveform breakdown voltage from 58 kV to 30 kV at constant P and d should allow the switch to hold off 30 kV 200 microseconds later. This would mean a recovery time of 200 microseconds. Triggering the switch is the only way to lower first waveform breakdown voltage at a given P and d.

In this paper, we will present data on triggered hydrogen spark gap recovery. The investigations will be carried out at 200 amp currents to test our ideas. The affect of gas pressure and gap spacing on first and second pulse breakdown voltage will be measured and the affect of trigger voltage on recovery will be investigated. Finally, the recovery of overvolted (trigger voltage = 0) and triggered spark gaps will be compared.

Apparatus and Procedure

Test Switch

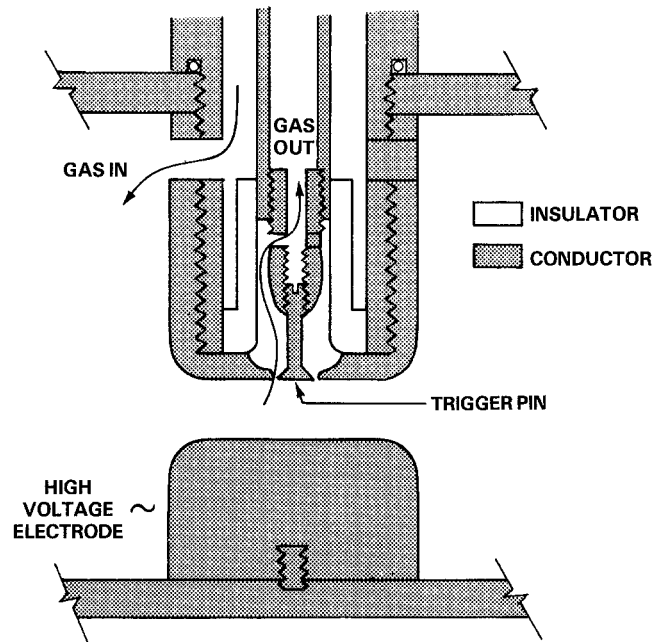
Figure 2: Triggered spark gap.

The switch under test consists of two opposing, 7.5 cm diameter brass electodes on cylindrical stubs protruding into the switch volume from two brass endplates. In the center of one electrode, there is a smoothed 0.6 cm diameter hole to allow the trigger pin fields access to the main gap volume (thus a trigatron type geometry). The two endplates are bolted into an epoxy-resin housing designed to withstand high pressures. Figure 2 gives the details.

Report Documentation Page

1. REPORT DATE **JUN 1987**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Triggered Spark Gap Recovery**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Surface Weapons Center Code F12 Dahlgren, va 22448**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**4**	

A gas handling system capable of providing variable pressure (0.76 to 51 ktorr) and low flow (1 cubic cm per sec) is connected to the gas inlet and outlet ports.

Test Circuit

The main gap test circuit consisted of two thyratron discharged 20 nfd capacitors, one fired some time after the other. The two voltage waveforms thus produced passed through a 1:5 step up transformer on their way to the 244 ohm current limiting resistor and the test switch. The details of this circuit are described elsewhere. [1] Main gap voltage is measured using a 16,000:1 Carborundum resistor voltage divider and main gap current was measured both with a .01 volt/amp current transformer and a .025 volt/amp CVR. The main gap circuit applied a negative polarity, .5kV/nsec, linearly rising voltage waveform across the main gap. The current from the resulting main gap discharge peaked at approximately 200 amps.

The trigger circuit consisted of a thyratron discharged capacitor as shown in Fig. 3.
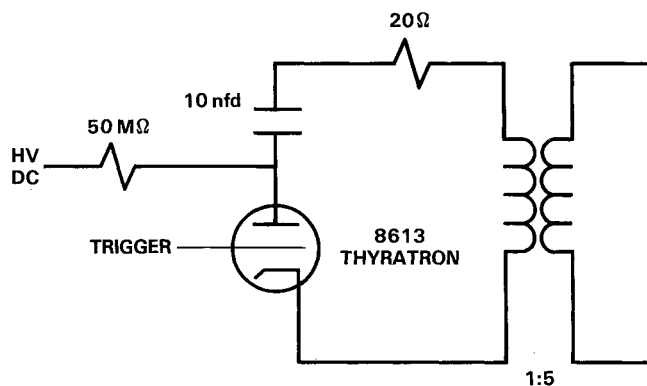

Figure 3: Trigger circuit

The trigger voltage was measured with a 1000:1 Carborundum resistor voltage divider and the current with both a .1 volt/amp current transformer and a .025 volt/amp CVR. The trigger circuit applied a positive polarity, .3 kV/nsec linearly rising voltage waveform across the trigger gap.

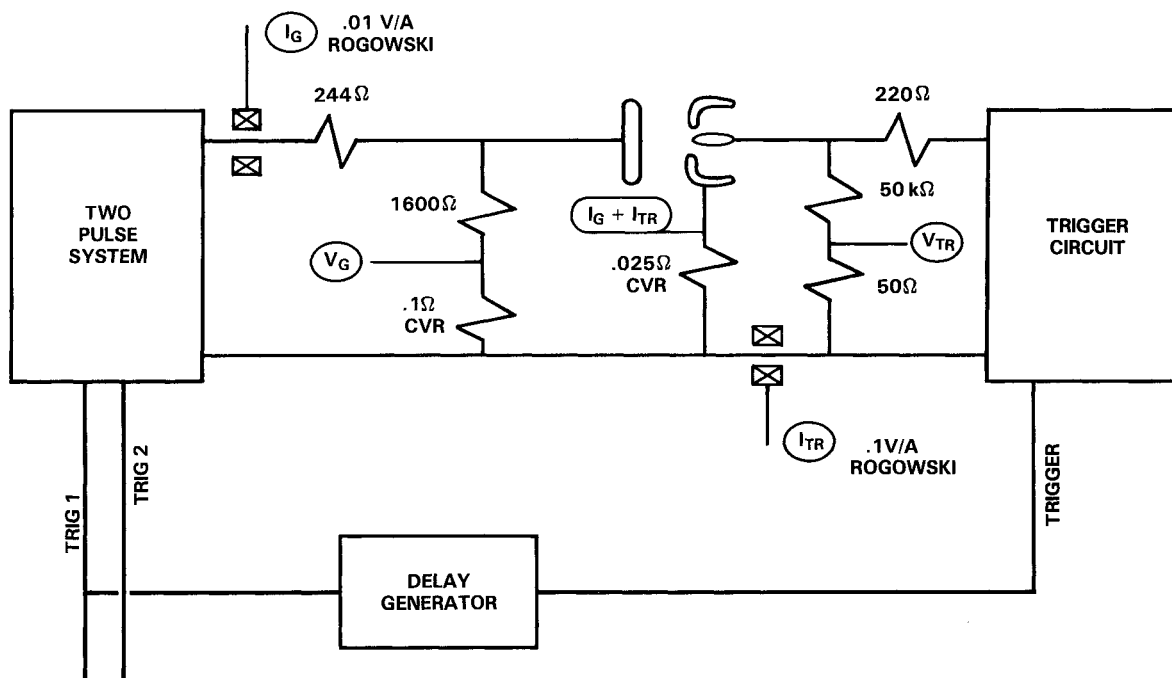The two circuits were interconnected as shown in figure 4.

Figure 4: Experimental apparatus used in testing the switch.

Test Procedure

Before each testing period, the spark gap was aged with several thousand shots to reduce statistical variations in the measurements.

The switch testing was performed by applying the negative polarity, .5 kV/nsec voltage waveform across the main gap. At any time during the rising portion of this applied voltage, a positive polarity, .3 kV/nsec voltage waveform was applied to the trigger pin. This caused the main gap to break down and pass a 200 amp current pulse. Both main gap and trigger gap currents and voltages are

measured. Some time after the first pulse, a second, negative polarity, .5 kV/nsec voltage waveform was applied across the main gap to probe the gap's recovery. The second waveform's breakdown voltage and the delay time was then measured.

Results and Discussion

P, d and Recovery

The recovery of the triggered spark gap was measured for various hydrogen pressures (3 - 20 ktorr), gap spacings (0.5 -1.5 cm), and

delay times (50 - 150 microseconds). At each pressure, gap spacing and delay time the second waveform's breakdown voltage was measured for twenty shots and averaged. A linear least squares fit was performed on the logarithms of these measured averages assuming that the second waveform breakdown voltage depends on powers of pressure, gap spacing and delay time. The result of this fit is:

$$V_{bd2} = (9.14 \times 10^{-3})P^{.77}d^{.78}t^{.44}$$

where second waveform breakdown voltage (V_{bd2}) is in kV, gas pressure (P) is in torr, gap spacing (d) is in cm, and delay time (t) is in microseconds.

Figure 5 shows the measured recovery of a hydrogen filled, triggered spark gap for a few values of gap spacing and pressure. The dotted lines on the graph represent the prediction of the fit.
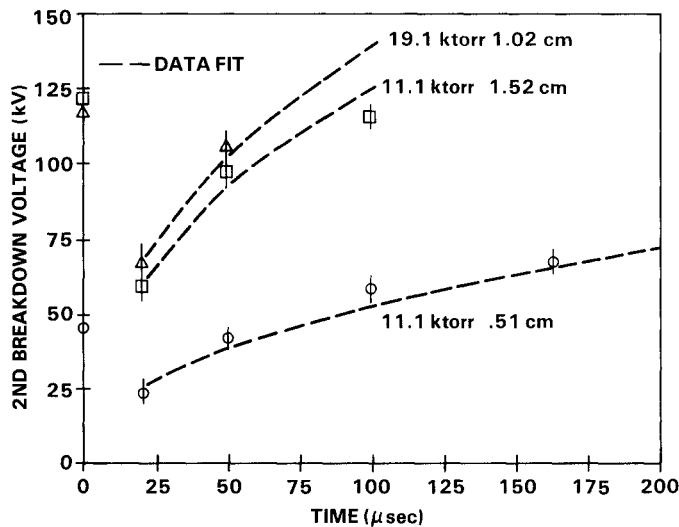

Figure 5: Recovery of a triggered hydrogen spark gap. The symbols along the vertical axis represent the first waveform breakdown voltage. The test system is limited to applying peak voltages less than 125 kV.

The recovery curve displayed in figure 5 with pressure 19.1 ktorr and gap spacing 1.02 cm (Pd= 19.5 x 10^4 torr-cm) indicates recovery to the first waveform breakdown voltage in about 75 microseconds. This order of magnitude improvement in spark gap recovery time compared to the overvolted case depends on two actions: simultaneously lowering the first waveform breakdown voltage and raising the second waveform breakdown voltage for a given delay time. The first waveform breakdown voltage is lowered below self breakdown voltage by increasing the voltage applied to the trigger pin. The second waveform breakdown voltage is increased by increasing P and d. Hydrogen gas also helps because, compared to most gases, its high thermal velocities allow fast removal of heat generated by the first breakdown.

By solving for Pd from the data fit and assuming V_{bd2}=100 kV, t=100 microseconds; one

can find pressures and gap spacings (Pd greater than 12.7 x 10^4 torr-cm) that display sub-100 microsecond recovery times for above 100 kV voltage pulses. However Pd cannot be indefinitely increased as the first waveform becomes more difficult to trigger at higher Pd. These limits require further investigation.

Triggering and Recovery

Overvolted recovery data gives a way to predict the recovery of triggered spark gaps, as was done from figure 1. Figure 6 is a plot of second waveform breakdown voltage versus delay time for an 11 ktorr, .5 cm spark gap. In one set of measurements, the first voltage waveform was triggered. In another set of measurements, the first voltage waveform overvolted the spark gap.

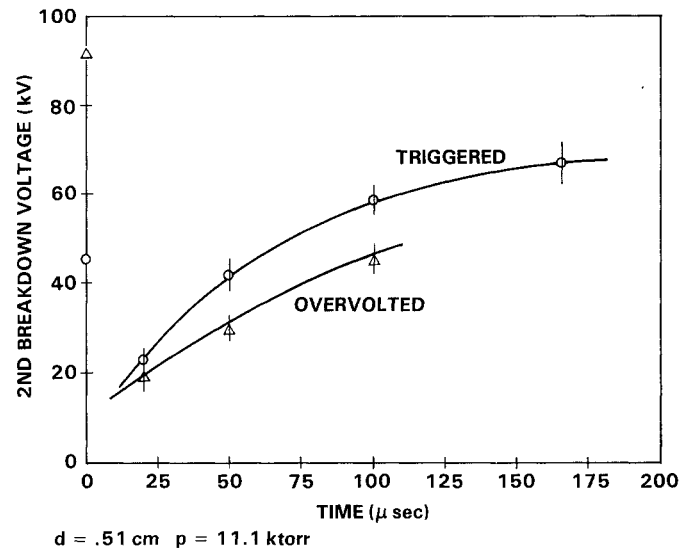d = .51 cm   p = 11.1 ktorr

Figure 6: Recovery of a hydrogen spark gap, triggered in one test and overvolted in another.

The current was measured to be the same for both cases. The important point is that the triggered spark gap recovers to a given voltage faster than the overvolted spark gap-faster than initially predicted.

The only difference between these two tests is that in one, the spark gap was triggered and in the other the spark gap was overvolted. This means that lower first waveform breakdown voltages and/or the existence of trigger fields speed gap recovery.

Spark gap recovery depends on the amount of energy deposited in the switching medium, the modes in which this energy is deposited, and the speed with which this energy is redistributed and removed. These processes depend explicitly on collisions. Since the products of a collision depend on the energy of the reactants and since the energy of the reactants depends on the electric field, it is conceivable that the amplitude of the electric fields applied to the switch should affect the energy distributed in the switch volume. Hence, the first waveform's trigger

may influence the amount and distribution of energy deposited in the switch, thus influencing the second waveform breakdown voltage.

Conclusion

By triggering a hydrogen spark gap, we can decrease the switch recovery time as compared to an overvolted gap. If we trigger the switch at voltages 50% below overvolted breakdown, the recovery time can be decreased from milliseconds for the overvolted case to < 100 microseconds for the triggered case. It has also been verified that increasing P and d increases the gap operating voltage to above 100 kV. Thus, it is possible to operate a 200 amp, low-flow spark gap switch with recovery times less than 100 microseconds and voltages above 100 kV.

It seems that triggering may do more than lower the first pulse breakdown voltage. Figure 6 indicates that triggering the spark gap actually speeds gap recovery compared to overvolted gaps. If this affect is due to the trigger; then, compared to the overvolted gap, the trigger must cause less energy to be deposited in the switch or the trigger must speed the deposited energy's removal. Perhaps the trigger speeds the formation of the first applied waveform's discharge, thus making the switch closure more energy efficient. This lower energy loss would allow faster recovery.

More investigation is needed to determine the limits of our approach. Limits must be found for operating voltage and recovery times. Presently work is proceeding to test the switch concept at higher currents (50 kA) and longer charge times (100 microseconds) on NSWC Dahlgren's PUPFAC, which is described in another paper at these proceedings.[2] Increasing jitter with more undervolting and higher pressures is a definite concern and detailed measurements must be performed. The strength of the trigger's affect on recovery needs further investigation as optimization of the trigger fields may further improve spark gap recovery.

Acknowledgements

References

1. Recovery of Overvolted Spark Gaps, Moran and Hairfield, 16th Power Modulator Symposium, June 1984.

2. A Facility for High Repetition-Rate Switch Testing at Medium Power, Moran, Hutcherson, Ball; 6th IEEE Pulsed Power Conference, June 1987.